THE NOnA DETECTOR
MEASURING q_{13} WITH THE NUMI BEAM

ROGER RUSACK

School of Physics and Astronomy, The University of Minnesota, 116 Church St SE, Minneapolis, Minnesota, 55455, USA.

For the NOνA Collaboration.

With the forthcoming operation of the NuMI beam the possibility of using the flux of neutrinos with a narrow energy range off the main NuMI beam axis to study $\nu_\mu \rightarrow \nu_e$ oscillations will become a reality. A new 50 kton detector to be built at a location of between 730 and 830 km from the Fermilab site is being proposed. The experiment is projected to be capable of a $>3\sigma$ detection of ν_e appearance for $\sin^2(2\theta_{13}) > 0.02$. This experiment also has promising prospects to address the neutrino mass hierarchy and CP-violation phase of the neutrino mixing. In this talk the current status of plans for the detector and the expected performance that can be achieved will be presented.

1. Introduction.

The study of the oscillation of muon-type neutrinos to electron-type neutrinos at a length scale of 1000 km is the main goal of the NOνA (**N**uMI **O**ff-Axis n_e **A**ppearance) experiment [1].

The significance of the search for these oscillations is that if they exist, that is if θ_{13} is not zero, then we will ultimately be able to determine the ordering of the neutrino masses and measure CP violation in neutrino oscillations. There is widespread belief that the very small neutrino masses are related to physics at an extremely high-energy scale, one that cannot be studied directly with accelerator beams, and it has also been speculated that CP violation by neutrinos could be one aspect of why the universe is composed solely of matter, rather than equal amounts of matter and antimatter. Thus while these measurements are very difficult to perform the theoretical motivation for them is highly compelling. This has lead to serious consideration of experiments to study this part of the neutrino sector in Japan, Europe and the US.

The NOνA experiment will make use of the Fermilab NuMI beamline and will build a new high-performance detector, whose primary physics goal will be the measurement of θ_{13} with approximately ten times more sensitivity than MINOS. To accomplish this we will have to increase the mass of the detector and optimize the design for the detection of ν_e interactions, all while containing the cost to be within reasonable bounds. To enhance the selection of $\nu_\mu \rightarrow \nu_e$ oscillations, the detector will be placed off the main axis of the beam at an angle where the energy of the neutrinos is more monochromatic.

When NOνA is operating we will search first for ν_e appearance with a neutrino beam and then subsequently run with an antineutrino beam. There are three unknown parameters to be measured — θ_{13}, the ordering of the mass states ($\Delta m_{31}{}^2$), and the parameter that measures CP violation (δ) — a third measurement will eventually be required in addition to neutrino and antineutrino measurements in NOνA to determine all three parameters. This third measurement could either be done by combining NOνA measurements with those taken elsewhere on different length baselines or by moving the NOνA detector, building an additional detector on the NuMI beamline, rebuilding the NuMI beamline to point in a slightly different direction. Since the JPARC I proposal [2] has been approved, the most natural process of untangling these parameters will be by combining the results of the two experiments. Furthermore, if a measurement of $\sin^2(2\theta_{13})$ is made at a reactor, where the value is insensitive to both the sign of $\Delta m_{31}{}^2$ and δ, the combination of all three sets of results could further clarify our understanding of this sector.

2. Physics Background.

Working within the assumption that sterile neutrinos either do not exist or do not mix with the active neutrinos, we can say that we have either no information or only upper limits on the parameters $\sin^2(2q_{13})$, the sign of $\Delta m_{31}{}^2$ and δ. Our lack of knowledge of the sign of $\Delta m_{31}{}^2$ is a statement of our ignorance of the whether the solar oscillation doublet (ν_1 and ν_2) is lighter (normal hierarchy) or heavier (inverted hierarchy) than the ν_3 state. All of these three unknown parameters significantly affect the rate of $\nu_\mu \rightarrow \nu_e$ oscillations that we would observe in our detector.

In addition to the oscillation parameters, the observed rate of ν_e interactions in the far detector is affected by the amount of material between the source and the detector. These matter effects have opposite sign for neutrinos and anti-neutrinos, for normal versus inverted hierarchies and are proportional to the amount of material traversed. By combining the neutrino results obtained with this experiment, where the effect will be ~±23%, and, say, JPARC I, where with its smaller baseline it will be ~±10% the neutrino hierarchy may be determined.

Given the complexity of the problem, it is highly unlikely that a single measurement with a long baseline detector sited at the first oscillation maximum would yield a unique set of values for the oscillation parameters. To completely untangle them a long range program of precision measurements made at different detectors sited at different distances from the neutrino source and at reactors will be required.

3. Overview of the Experiment.

3.1. *The NUMI Beam.*

The NuMI neutrino beamline is currently under construction at Fermilab and is expected to become operational in early 2005 becomes operational in early 2005. In it the 120 GeV protons from the Main Injector accelerator are used to produce a secondary beam of pions and kaons that travels through a 675 m long evacuated decay pipe. This is followed by a cooled beam stop and 240 m of earth before the near detector hall. The resultant neutrino beam has a 3.3^{o} downward slope aiming at the MINOS detector in northern Minnesota. The primary target has been designed for 0.4 MW of incident proton beam power and should, with minor modifications, be able to sustain higher intensities.

The NOνA experiment will make use of a kinematic feature of neutrino beams that at small angles away from the central beam axis the beam energy is nearly monochromatic, first proposed for the BNL experiment E-889 [3]. In pion decay in flight to a muon and a neutrino, the neutrino's energy (E_n) is given by:

$$E_n = \frac{0.43 E_p}{1+g^2 q^2}$$

where θ is the angle between the pion and the neutrino directions and E_p is the pion energy. Thus at some production angles a wide range of pion energies contribute neutrinos with approximately the same energy. In figure 1 the implementation of this scheme is shown for angles of 7, 14 and 21 mr off the central axis.

The narrow neutrino energy spread can then be exploited in a ν_e appearance experiment to separate ν_e interactions from backgrounds, which tend to have a broader energy distribution. Furthermore, by building the detector at a specific angle from the beam's central axis, the optimum energy for the experiment can be selected.

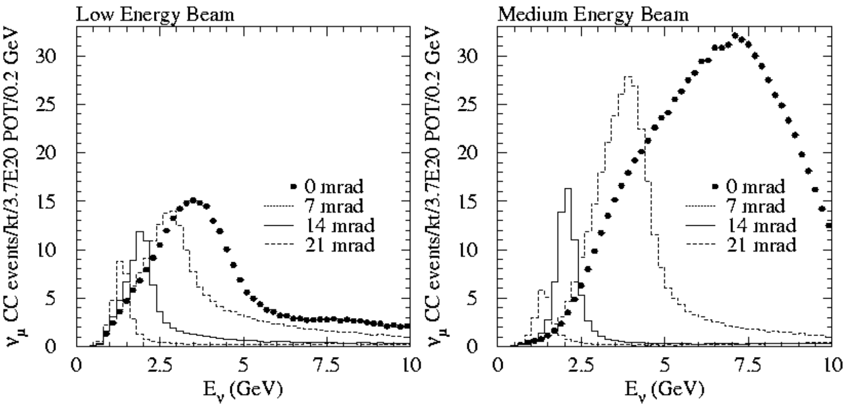

Figure 1 Charged current ν_μ event rates expected under a no-oscillation hypothesis at a distance of 800 km from Fermilab and at various transverse locations for the NuMI low-energy beam configuration (left) and medium-energy beam configuration (right)

3.2. *The detector.*

The NOνA detector is designed to detect ν_μ ? ν_e oscillations with high precision in the atmospheric neutrino mass squared region. The signal for ν_e's will be their charged current interactions, which will be identified by the presence of an electron. This signal has two types of backgrounds, one from intrinsic ν_e's that are naturally present in the beam at the level of ~0.7%, and a second from misidentified neutral current ν_μ events, or high *y* ν_μ charged current events, where a π^o fakes the electron signature. The intrinsic ν_e's background can be suppressed further by measuring the electron's energy, which will be broad, and the background from π^o's can be suppressed with good pattern recognition in the event.

Thus the requirements for the calorimeter are good energy resolution and precision tracking. Low-Z material is required to allow the track of the electron, which will have an energy of ~1 GeV, to be followed in several detector layers. This allows the electron's track to be identified and the fluctuations in the track direction to be measured. Additionally, the size of the detector must be very large, ~50,000 tons for there to be a sufficient number of interactions to provide the needed statistically significance. Since the objective is to observe the appearance of ν_e's there will be two detectors, like MINOS, one near to, and another one far from the neutrino source.

The collaboration has investigated in detail two types of tracking calorimeter. For both, the passive low-Z material is wood, either as particle board or as Oriented Strand Board. The first is made from sawdust and the second is made form wood chips. They are both produced in large quantities in northern Minnesota, are relatively cheap and, since they are composed mostly of carbon, meet our low-Z requirement. Two active mediums have been investigated, liquid scintillator read out with wavelength-shifting plastic fibers, and glass resistive plate chambers. After extensive design and simulation studies, the collaboration has selected the liquid scintillator option as the baseline detector. Recently, as the possibilities of the liquid scintillator option have become better understood, a smaller (20,000 ton) liquid scintillator calorimeter consisting only of active elements is now receiving serious consideration..

The baseline far detector will consist of 42,000 tons of wood, 6,900 tons of liquid scintillator inside 1,800 tons of white extruded PVC tubing for a total of 50,000 tons. The scintillator and absorber will be arranged in planes 14.6 m high, 29.3 m wide and 0.23 cm (0.3 radiation lengths) thick. The PVC extrusions will consist of 14.6 m long tubes 25.6 mm wide and 39.6 mm deep. A single 0.8 mm diameter wavelength-shifting fiber running the full length of the PVC tube and looping back along the tube, will be used to collect the scintillating light. Both ends of the looped fiber will be coupled to a single pixel of an avalanche photodiode (APD) array[a] cooled with a thermo-electric cooler to -15^{o}C to reduce the dark current. Seven hundred and fifty planes will be arranged perpendicular to the beam axis, with alternating orthogonal views, for a total of length 170 m and total of ~600,000 electronic channels. Unlike MINOS, the far detector will be built on the surface with active shielding placed above it. Our calculations of the background levels from cosmic rays indicate that they will be acceptably low; due mostly to the very short beam spill, which is 10 μsec every 2 seconds.

The selection of the site of the detector is constrained by the optics of the NUMI beam, which dictates a practical range of ~700 km to ~900 km. At a distance of ~12 km from the beam's axis, the most probable energy is ~2 GeV. The optimal distance from Fermilab, the first oscillation maximum, is then be determined by the value of Δm_{23}^2. Since the matter effects are enhanced with a longer baseline we prefer to be on the higher side of the uncertainty in this number. Finally the site needs to have the necessary infrastructure to construct and operate a 50,000 ton detector in all seasons. After a study of several possible sites our preference is for one on the Ash River Trail, about 40 km south of the Canadian border and 820 km from the neutrino source. The site of the near detector will be located in the NUMI access tunnel, upstream of the MINOS near detector.

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[a] Hamamatsu Photonics, Silicon APD Array, S8550.

4. Physics Potential.

Figure 2 shows the calculated three standard deviation discovery limits for ν_μ ? ν_e oscillations assuming that Δm_{32}^2 = 0.0025 eV². The vertical axis represents the fraction of possible δ values for which a 3-σ discovery could be made, *i.e.* 1 is the least favorable and 0 is the most favorable. The continuous line represents the limits for five years of operation with the current machine parameters, 20×10^{20} protons on target, while the dotted lines represent the sensitivity for a factor of five increase in luminosity. Each luminosity assumption has a pair of lines; the one to the left is for normal mass hierarchy, while the one on the right is for an inverted hierarchy.

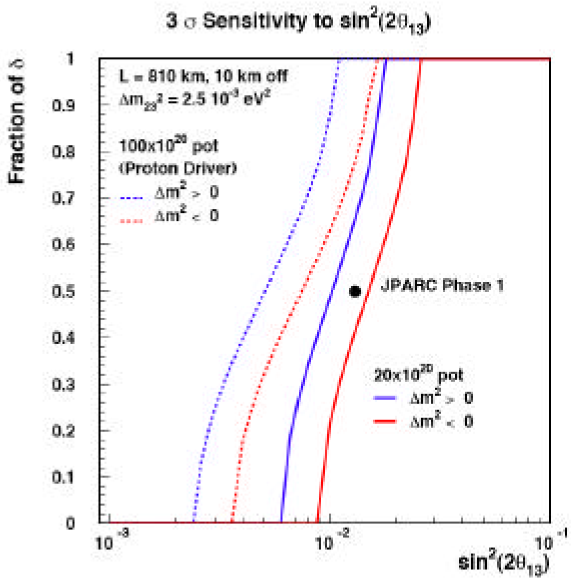

Figure 2. Three standard deviation discovery limits for the observation of ν_μ ? ν_e oscillations. See text for details.

References

1. I. Ambats *et al*. "Proposal to Build an Off-Axis Detector to Study ν_μ ? ν_{e} - Oscillations in the NUMI Beamline." FNAL-Proposal-929.
2. JPARC I, Letter of Intent, January, 2003. http://neutrino.kek.jp/jhfnu/.
3. The E889 Collaboration, "Long Baseline Neutrino Oscillation Experiment at the AGS" BNL report No. 52459.